

BGA Reliability Tests- Findings of JPL-led BGA Consortium

Reza Ghaffarian
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

INTRODUCTION

The Jet Propulsion Laboratory (JPL)-led-consortium with sixteen team members was established in early 1995 to evaluate the quality and reliability of ball grid arrays (BGAs) and to help build the infrastructure necessary for implementation of this technology for aerospace applications.¹ Diverse membership from military, commercial, academia, and infrastructure sectors (JPL's members) allowed in a concurrent engineering approach to resolve many challenging technical issues.

Nearly 200 test vehicles, each with four packages, were assembled and tested using an experimental design. The most critical variables incorporated in this experiment were package type, board material, surface finish, solder volume, and environmental condition. The packages used for this experiment were commercially available packages with over 250 I/Os including both plastic and ceramic BGA packages.

The test vehicles were subjected to thermal and dynamic environments representative of aerospace applications. Two different thermal cycling conditions were used, the JPL cycle ranged from -30 °C to 100 °C and the Boeing and EMPF ranged from -55 °C to 125 °C. Dynamic conditions simulated the launch requirements for the JPL New Millennium Project. The test vehicles were monitored continuously to detect electrical failure and their failure mechanisms were also characterized.

Currently, a number of the packages in the test vehicles have accumulated more than 2,000 cycles with no solder joint failure. Extensive analysis was performed to understand failure during thermal cycling and to determine the influence and criticality of experiment variables. The test vehicles were removed periodically for optical inspection, Scanning Electron Microscopy (SEM) evaluation, and cross-sectioning for crack propagation mapping. Failure mechanisms for the two environments were

documented. Data collected from three facilities were analyzed and fitted to distributions using the Weibull distribution and Coffin-Manson relationships for failure projection. This paper will describe package characterization results including coplanarities for ceramic and plastic packages as well as results of process optimization including X-ray images. In addition JPL's cycles to failure and their Weibull parameters for the 625 I/O CBGAs subjected to two thermal cycling, one using a NASA cycle with 245 minute duration, will also be presented.

BALL GRID ARRAYS

Background

BGA is an important technology for utilizing higher pin counts, without the attendant handling and processing problems of the peripheral array packages (PAP). Unlike PAPs, BGAs have balls, covering the entire area, or a large portion of the area on the bottom of the package.

BGAs offer several distinct advantages over Fine Pitch (FP) and Ultra Fine Pitch (UFP) Surface Mount Components (SMCs) that have gull wing leads, including:

- High pin counts, generally > 200.
- Larger lead pitches, reduction in manufacturing complexity.
- Higher packaging densities, area for BGAs vs. periphery for leaded.
- Faster circuitry, balls are much shorter than leads.
- Better heat dissipation, lower path from die to PWB for vs. leaded.

BGAs are also robust in processing. This stems from their higher pitch (0.050 inch typical), better lead rigidity, and self-alignment characteristics during reflow processing.

BGAs, however, are not compatible with multiple solder processing methods and individual solder

joints cannot be inspected and reworked using conventional methods. In ultra low volume SMT assembly applications, e.g. NASA's, the ability to inspect the solder joints visually has been standard and has been a key factor for providing confidence in solder joint reliability.

Objectives

Objectives of the program were narrowed to meet the team members' needs with consideration of industry projection for this technology. Based on the relationship between pin count and cost/performance, it was apparent that peripheral leads will fall short of meeting advanced packaging requirements. Cost/performance requirements for QFPs to meet near term future requirements were even more disparate. However, for BGAs there was a wide range of I/O, pitch, and sizes meeting both a near term demand and expected future long term requirements.

After extensive discussion and further ranking of the variables discussed, the following most critical issues were identified:

- Determine a suitable inspection technique for BGA packages, particularly after they have been attached to the substrate. Evaluate:
 - X-ray systems
 - Acoustic imaging systems
 - Visual inspection for peripheral solder joints
- Decide the optimal package type array configuration.
 - Peripheral array versus full area array and depopulated packages
 - Overmolded plastic vs. metallic version (Super BGA)
- Characterize the reliability differences between ceramic and plastic BGAs.
 - Thermal cycling including a military version and power cycling
 - Vibration behavior
 - Robustness and reliability compared to fine pitch QFP
- Assess the various techniques for reworking AAP/BGA packages.

Packages

Packages cover the range from OM PAC to SuperBGAs. In SBGA, the IC die is directly

attached [0 an oversize copper plate providing a better heat dissipation efficiency. The copper plate also acts as a stiffener and ground plane for the package, The solder balls for plastic packages are eutectic (63Sn/37Pb).

Ceramic packages with 625 I/Os and 361 I/Os were include in our evaluation. Ceramic solder balls have 0.035 inch diameters and have a high melting temperature (90Pb/10Sn). These balls are attached to the ceramic substrate with eutectic solder (63 Sn/37Pb) material. At reflow, substrate eutectic material and the PWB eutectic paste reflow to provide the electro-mechanical interconnects.

Figures 1 shows Scanning Electron Micrograph (SEM) photos of ceramic packages with straight and tilted solder balls. Figure 2 shows X-ray of similar packages with signs of minor [0 strong tilts,

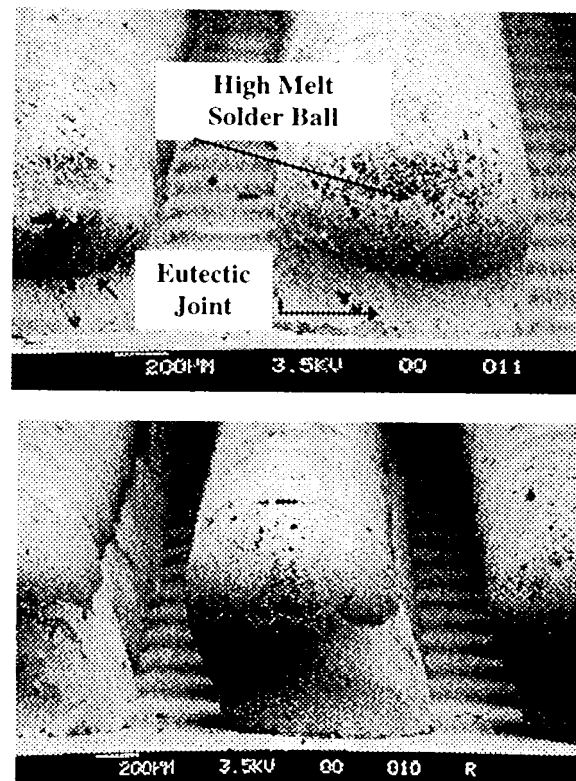


Figure 1 Solder Balls With No Tilting (top) and With Tilt in CBGA

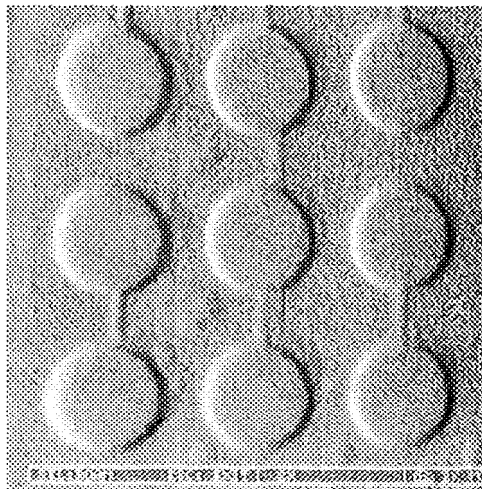
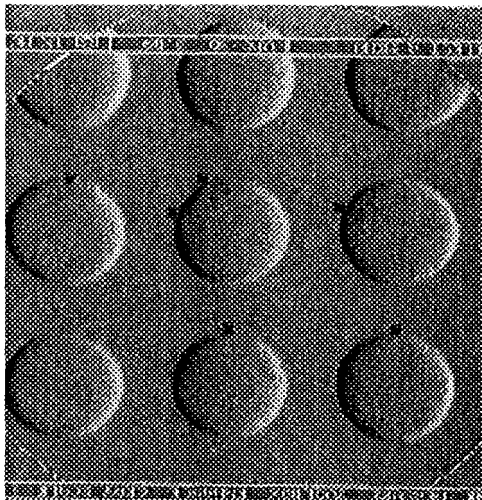


Figure 2 X-ray of Solder Balls With No Tilt and With Tilt in CBGA

Package Dimensional Characteristics

Package dimensional characteristics are among the key variables that affect solder joint reliability. Dimensional characteristics of all packages were measured using a 3D laser scanning system. Output of measurements included solder ball diameter, package warpage, and coplanarity².

Package coplanarity is defined as the distance between the highest solder ball (lead for QLP) and the lowest solder ball. In 3D laser technique, planarity of individual balls are calculated relative to seating plane formed from the three tallest balls. Table 1 summarizes planarity results.

Table 1 Planarities of Ceramic and Plastic Packages

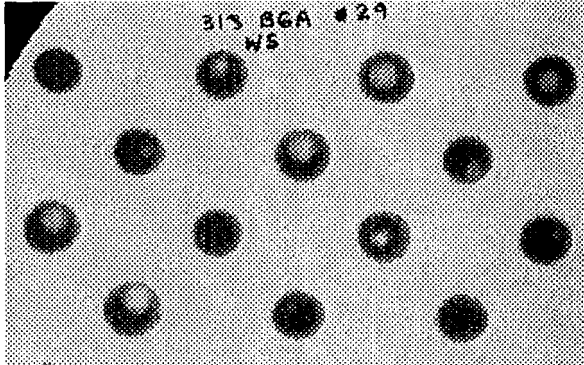
Package Type	Coplanarity Range (inch)
CBGA 625	.0015-.002 for 104 .0030-.004 for 4
CBGA 361	.0012-.0022 for 102
560 SuperBGA	.002-.004 for 72 .004-.006 for 45 .006-.0077 for 4
352 SuperBGA	.0014-.0037 for 145 .0048,.0058,.0065,.009 1
352 OMPAC	.0024-.0057 for 128
313 OMPAC	.0022-.0052 for 140
2S6 OMPAC	.0021-.0047 for 140

Test Vehicle Assembling

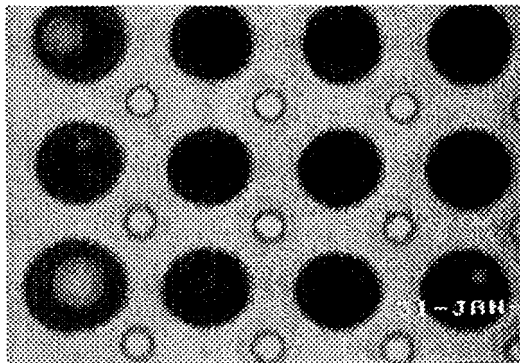
Full assembling were implemented after process optimization from the trial test. The following procedures were followed:

- PWBs were baked at 125°C for 4 hours prior [0 screen printing.
- Two types of solder pastes were used an RMA and water soluble.
- Pastes were screen printed and the heights were measured by laser profilometer.
- A 10 zone convection oven was used for reflowing.
- The first assembled TV using an RMA reflow process was visually inspected and X-rayed to check solder joint quality.
- All assemblies were X-rayed
- Interchangeability of reflow profile for RMA and Water Soluble solder pastes were examined. One TV with water soluble solder paste was reflowed using the RMA reflow profile. The solder joints showed much higher void content than expected (Figure 3) as well as signs of flux residues. Figure 4 shows X-ray images when an RMA reflow profile was used for the RMA solder paste. The latter showed much lower void levels which were sporadic rather a large void observed in the former images.
- For water soluble, a new reflow profile was developed based on manufacturer's recommendation. This reflow process was used for the remaining of the test vehicles.

- Assemblies with water soluble flux were cleaned in an Electrovert 11500. Those with RMAs cleaned using Isopropyl Alcohol (IPA) and a 5% saponifier.
- All fine pitch 256 QFPs had to be reworked for bridges. An X-ray example shown in Figure 5.

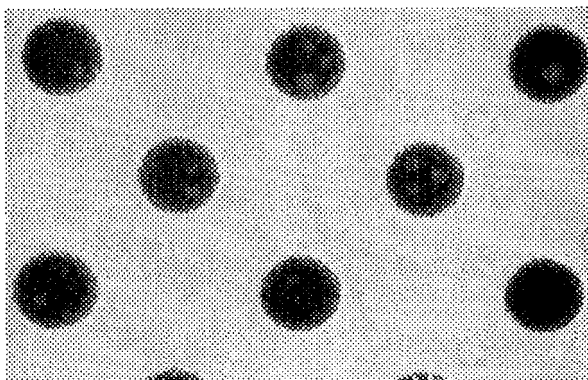


a) Excessive Voids in 313 PBGA

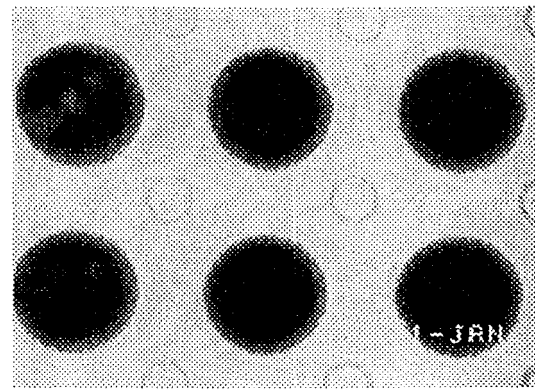


b) Excessive Voids in 352 SPBGA

Figure 3 Excessive Voids for Water Soluble with an RMA Reflow Profile



a) Reduced Voids in 313 PBGA



b) Reduced Voids in 352 SPBGA

Figure 4 Voids for Water Soluble Paste with a Water Soluble Reflow Profile

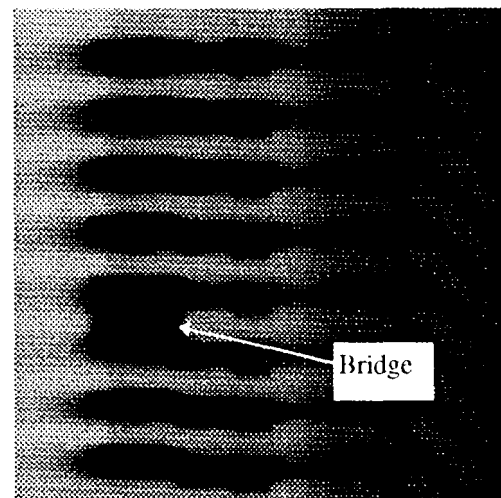


Figure 5 X-ray Photo Shows a Bridge in the 256 Fine Pitch (16 roll) QFP

BGA Thermal Cycling Results

To link our data with those of conventional SMT test results performed at JPL under another program³, a set of ceramic assemblies were subjected to a NASA cycle with long duration time that have widely been used for qualification testing and also was used in JPL's previous solder joint studies.

This long duration cycle starts at 25°C with a decrease rate of 2°C per minute to -55°C with an own dwell setting of 45 minutes. The temperature increase to 100°C at a rate of change of 0.1 2°C per minute with an oven dwell setting of 45 minutes, followed by a decrease of temperature to 25°C

completes the cycling. The duration of one cycle is 246 minutes.

Figure 6 compares cycles to failure for CBGA 625 I/Os and 68-, 28-, and 20-pin ceramic Leadless (LCC) assemblies subjected to this cycle. Only for this set of CBGA assemblies, failures were detected manually. Test vehicles were removed periodically and daisy chain resistances were measured for opens.

Other BGA test vehicles were continuously monitored through a LabView system designed for this purpose⁴. For LCCs, failures were detected by Anatech® and verified by visual inspection. The failure distribution percentiles were approximated using a median plotting position, $P_i = (i - 0.3) / (n + 0.4)$.

As expected, there was a large spread in cycles to failure because of variance in board materials (FR-4 and Polyimide for CBGAs, FR-4 for LCCs), solder joint volume, quality and location. The first failure for CBGA was detected at 312 cycles and occurred

between 292 and 312 cycles. The last failure detected between 450 and occurred between 439 and 450 cycles. The Weibull cumulative failure distribution was used to fit cycles to failure data. The Weibull scale and shape parameters for CBGA were 391 cycles and 8.4 respectively

Figure 7 includes cycle to failure test results for CBGA 625 I/Os assemblies on polyimide and FR-4 PWBs with different surface finishes as well as different solder volumes. These assemblies were thermally cycled between -30°C and 100°C with 82 minute duration. The thermal cycling oven temperature settings and temperature profile is also shown. Daisy chains of test vehicles were continuously monitored for failure detection. The 2P Weibull scale and shape parameters were 424 and 9.1. Five highest points, four representing those with Ni/Au and one with high solder volume, were excluded in order to get a better fit to data,

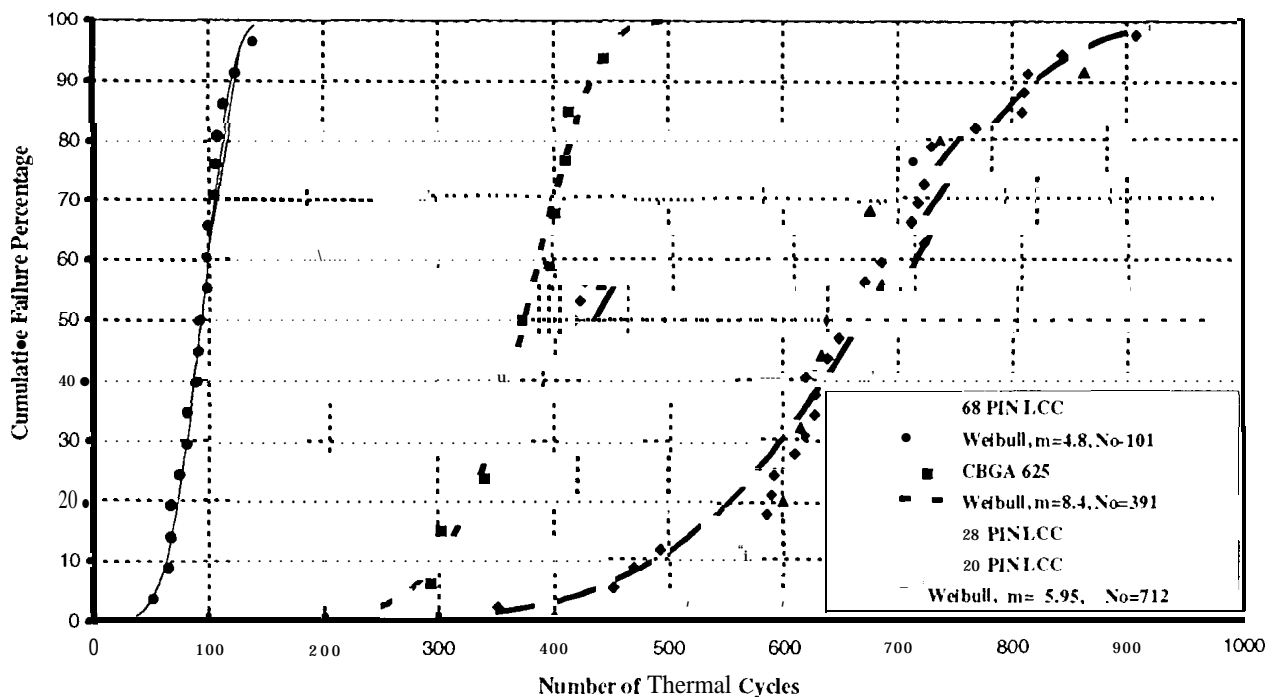


Figure 5 Cumulative Failure Distribution Plots for CBGA 625 I/O and LCC Assemblies Subjected to -55 °C<->100°C with 245 minute duration

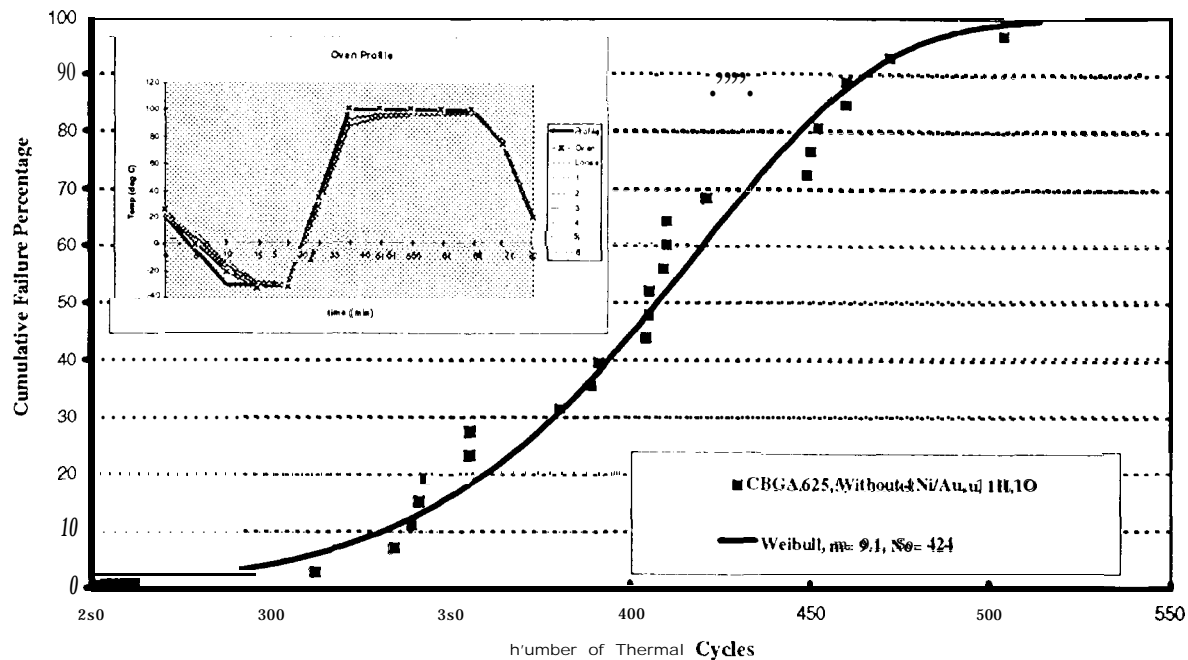


Figure 6 Cumulative Failure Distribution Plots for CBGA 625 I/O and LCC Assemblies Subjected to -30°C<->100°C with 82 minute duration

Conclusions

- Ceramic packages showed lower warpages and were more coplanar than their PBGA counterparts. Numerous ceramic packages had tilted solder balls.
- Solder ball planarities were significantly higher for plastic than for ceramic packages. A few PBGAs showed unexpectedly higher values above their norm distribution. PBGAs, however, are more robust and the large planarity values might not be as detrimental to the solder joint reliability as those for ceramics. Some planarity differences among the PBGA balls are accommodated by their collapses during the reflow process. This is not the case for CBGAs where high melt solder balls remain intact during reflow. The solder ball diameter controls the stand-off height which is a key factor to solder joint reliability.
- The BGA void levels were the same as those generally observed by industry. As expected, BGAs were robust in assembling compared to the 256 fine pitch, 0.4 mm, QIPs. All QIPs

showed bridging to some degree and had to be reworked..

- RMA and water soluble reflow profiles were significantly different and they should be optimized separately for the applications. Large rather smaller and sporadic voids were generated when an RMA reflow profile for a water soluble solder paste was used.
- 3D laser scanning is excellent for characterization of package dimensions, but possibly not for solder ball measurement.
- Cycles to failures for a NASA cycle (-55°C to 100°C) and a modified version used for BGA (-30°C to 100°C) did not follow a Coffin-Manson relationship. Data set showed an almost a linear reduction with delta temperature rather than a near cube power reduction projected by the model.
- Cycles to failure indicate that the choice of cycle selected (-30°C to 100°C) for time and cost effectiveness was appropriate.
- Cycles to failure results for two temperature profiles are in agreement with the school of thoughts that suggest low temperature exposure

is of less critical than high temperature and time beyond the creep threshold at high temperature have no significant effects on eutectic solder joint failure.

REFERENCES

1. R. Ghaffarian, "Area Array Technology Evaluation for Space and Military Applications", The 1996 International Flip Chip, Ball Grid Array, TAB and Advanced Packaging Symposium Proceeding, Feb. 13-16, 1996.
2. R. Ghaffarian, "CBGA/PBGA Package Planarity and Assembly Reliability", The 1997 International Flip Chip, Ball Grid Array, TAB and Advanced Packaging Symposium Proceeding, Feb. 17-19, 1997.
3. "The Interplay of Solder Joint Quality and Reliability for Leaded and Leadless Components," Ninth Annual Soldering Technology for Electronic Packaging Symposium, Oct. 21-25, 1996, Binghamton, NY
4. "Reliability Investigation of Ball Grid Assemblies for Space Flight Applications," Proceedings of the Technical Program, NIPCON West '97, Page 46-52

ACKNOWLEDGMENTS

The research described in this publication is being carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and space Administration.

Thanks to Sharon Walton and for monitoring environmental testing at JPL. Acknowledge in-kind contributions and cooperative efforts of BGA consortium team members including: P. Barela, K. Bonner, K. Yee, S. Bolin, C. Bodie, S. Walton, *JPL*; M. Andrews, *ITRI*; S. Lockwood, M. Simeus, P. Drake, *HMSC*; I. Sterian, B. Houghton, *Celestica*; M. Ramkumar, *RIT*; S. Levine, R. Lécresse, *Altron*; P. Mescher, *AMKOR*; Dr. N. Kim, *Boeing*; W. Goers and J. Mearig, *EMPF*; M. Cole, A. Trivedi, *IBM*; and 'I'. Tarter, *AMD*; F. Schlieper, C. Walquist, *Nicolet*; R. Dudley, R. Balduf *View Engineering*. My deepest appreciation to others who had been or are being contributors to the progress of both programs.